

A Feasibility Study for Simultaneous Estimates of Water Vapor and Precipitation Parameters Using a Three-Frequency Radar

R. MENECHINI

Instrument Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland

L. LIAO

Goddard Earth Science and Technology Center, and Caelum Research Corporation, Greenbelt, Maryland

L. TIAN

Goddard Earth Science and Technology Center, and University of Maryland, Baltimore County, Baltimore, Maryland

(Manuscript received 7 February 2005, in final form 20 May 2005)

ABSTRACT

The radar return powers from a three-frequency radar, with center frequency at 22.235 GHz and upper and lower frequencies chosen with equal water vapor absorption coefficients, can be used to estimate water vapor density and parameters of the precipitation. A linear combination of differential measurements between the center and lower frequencies on one hand and the upper and lower frequencies on the other provide an estimate of differential water vapor absorption. The coupling between the precipitation and water vapor estimates is generally weak but increases with bandwidth and the amount of non-Rayleigh scattering of the hydrometeors. The coupling leads to biases in the estimates of water vapor absorption that depend primarily on the phase state and the median mass diameter of the hydrometeors. For a down-looking radar, path-averaged estimates of water vapor absorption are possible under rain-free as well as raining conditions by using the surface returns at the three frequencies. Simulations of the water vapor attenuation retrieval show that the largest source of error typically arises from the variance in the measured radar return powers. Although the error can be mitigated by a combination of a high pulse repetition frequency, pulse compression, and averaging in range and time, the radar receiver must be stable over the averaging period. For fractional bandwidths of 20% or less, the potential exists for simultaneous measurements at the three frequencies with a single antenna and transceiver, thereby significantly reducing the cost and mass of the system.

1. Introduction

Many remote sensing techniques are being used experimentally or operationally to estimate atmospheric water vapor. These include radiometers at microwave (Westwater et al. 2001; Solheim et al. 1998; Schultz et al. 1993; Schlüssel and Bauer 1993), millimeter-wave (Rosenkranz 2001; Wang et al. 1995; Wilheit 1990) and IR (Schmetz and Turpeinen 1988; Hagen et al. 2004) wavelengths; Raman lidar and differential absorption lidar (DIAL) (Whiteman 2003; Behrendt et al. 2002;

Brassington 1982); and GPS-based techniques (Bevis et al. 1992; Alber et al. 1997). With a few possible exceptions (e.g., Liljegren 2004), most of the instruments and retrieval methods are not applicable in the presence of rain. In fact, the measurement of water vapor in rain is difficult even with conventional rawinsondes. Nevertheless, its estimation is important in microphysical studies and in the evaluation of cloud models.

Although little work has been done on water vapor estimation using radar, an exception is the work of Tian et al. (2004) who have analyzed dual-frequency (10 and 94 GHz) airborne Doppler radar data. By deriving the hydrometeor size distribution from the Doppler velocities and then modifying the radar reflectivity factors Z to account for Mie scattering and hydrometeor attenuation, the attenuation from cloud and gases can be in-

Corresponding author address: Robert Meneghini, Instrument Sciences Branch, Code 614.6, NASA/GSFC, Greenbelt, MD 20771.

E-mail: bob@neptune.gsfc.nasa.gov

ferred from the difference in the modified Z values at the two frequencies. In this paper, a three-frequency radar is studied for which one of the frequencies is taken at the 22.235-GHz line center with the others chosen at a lower and higher frequency with equal water vapor absorption coefficients.

Equations for estimates of water vapor absorption and precipitation and cloud attenuation are given in section 2, followed by a simulation and error analysis of the water vapor absorption and density estimates in section 3. Discussions on the algorithm and radar implementation are given in section 4.

4. Discussion and summary

The approach used here has some similarities to the differential absorption lidar technique in that it uses frequencies on and off line center to estimate the strength of absorption. The fact that precipitation is the background scattering medium, however, implies that the differential attenuation by hydrometeors can easily be as large as water vapor absorption; moreover, non-Rayleigh backscattering effects at these frequencies can be comparable in magnitude to attenuation and absorption. By the use of three frequencies, we can take advantage of the fact that differential attenuation from precipitation and cloud is approximately an odd function with respect to the center frequency while the differential water vapor absorption is approximately an even function.

In deriving an expression for the differential vapor absorption, the critical assumption is that the differential attenuation from cloud and precipitation between the upper and lower frequencies can be expressed as a fraction of the differential attenuation between the center and lower frequencies. Results of the simulations show that this assumption leads to biases in the estimate of water vapor density that become larger as the bandwidth increases. Although the biases are small in snow, they are particularly strong in the melting layer and lead to large negative biases in the vapor density estimates in and around the melting layer.

Although the focus of the paper is estimation of water vapor, the approach also offers the potential of precipitation estimation. Because of the choice of lower and upper frequencies, the differential measured reflectivity factor $\tilde{Z}_m(f_u) - \tilde{Z}_m(f_l)$ is a function only of the characteristics of the precipitation and cloud and is independent of water vapor. If the differential path attenuation from cloud and precipitation can be estimated, then $\tilde{Z}(f_u) - \tilde{Z}(f_l)$ follows directly from (10). It is clear from the results of Fig. 3 and Fig. 5, however, that from $\tilde{Z}(f_u) - \tilde{Z}(f_l)$ an estimate of the D_0 can be obtained. Moreover, an estimate of the number con-

centration N_t can be obtained from the radar equation (1). To start the procedure requires an initial or estimated path attenuation. One such estimate can be obtained from (21) by measuring the surface return powers in clear regions. However, as recently shown by Mardiana et al. (2004), the equations also can be solved iteratively without an independent path-attenuation estimate. In either case, the procedure yields estimates of the hydrometeor size distribution parameters in range. The D_0 and N_t values can be used, in turn, to improve the estimate of the differential water vapor absorption by providing estimates of the bias terms E_1 and E_2 . A drawback to the procedure is that the equation for N_t , as derived from the radar equation, is a function $k_v(f_l)$ or $k_v(f_u)$. Although this term is usually small relative to the hydrometeor attenuation for the 20% and 30% bandwidth cases, it represents an additional error source in the precipitation retrieval problem. In principle, just as the hydrometeor size distribution parameters can be used to correct for biases in the water vapor retrieval, the water vapor retrieval can be used to account for this contribution in the precipitation retrieval. Whether iterating between solutions to the precipitation and water vapor equations will provide stable solutions is not clear, however.

Another way to view the technique is as a variation of the differential-frequency implementation. In this approach, a single antenna and transceiver are used to transmit and receive signals at more than one frequency. However, this requires a wideband power amplifier and a wideband antenna. Wideband power amplifiers with bandwidths up to 20% are now available in some frequency bands (J. Carswell 2004, personal communication). For broadband solid-state amplifiers, with high duty cycles but low peak powers, pulse-compression techniques can be used to achieve a fine range resolution. Averaging the data to a coarser vertical resolution may provide a sufficient number of independent samples to make the measurement technique feasible without excessive space or time averaging. One other way of increasing the effective number of independent samples is by the use of data whitening (Koivunen and Kostinski 1999; Torres and Zrnić 2003). Another requirement of the radar would be well-matched beamwidths at the three frequencies. Because the total differential path absorption for a 20% bandwidth is on the order of 1 dB, any mismatches in the radar resolution volumes will have a strong effect on accuracy, particularly in convective rain where vertical and horizontal gradients in the reflectivity field can be large. Horn-lens and parabolic antennas are inherently broad band and should be capable of good performance over a 20% bandwidth. Nevertheless, detailed calculations would be needed to assess the degree of beam matching needed relative to the gradients in the reflectivity field.